Bimodal Nuclear Thermal Rocket Analysis Developments

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Agenda

- Introduction
  - Nuclear Cryogenic Propulsion Stage (NCPS) Project
  - Nuclear Thermal Propulsion and Bimodal Reactors
  - Analysis Methodology
- NERVA Systems
  - Overview of NERVA fuel element/tie tube
  - Proposed system diagram
  - Tie tube exit temperatures issues
- ESCORT System
  - Power Mode Analysis
- Conclusions

Introduction

- Nuclear Thermal Propulsion (NTP) preferred technology for manned mission to Mars [1]
- NCPS researching small 33.4 kN (7.5 klbf) engines for flight demo and robotic missions
- and 111.2 kN (25 klbf) engines for human missions

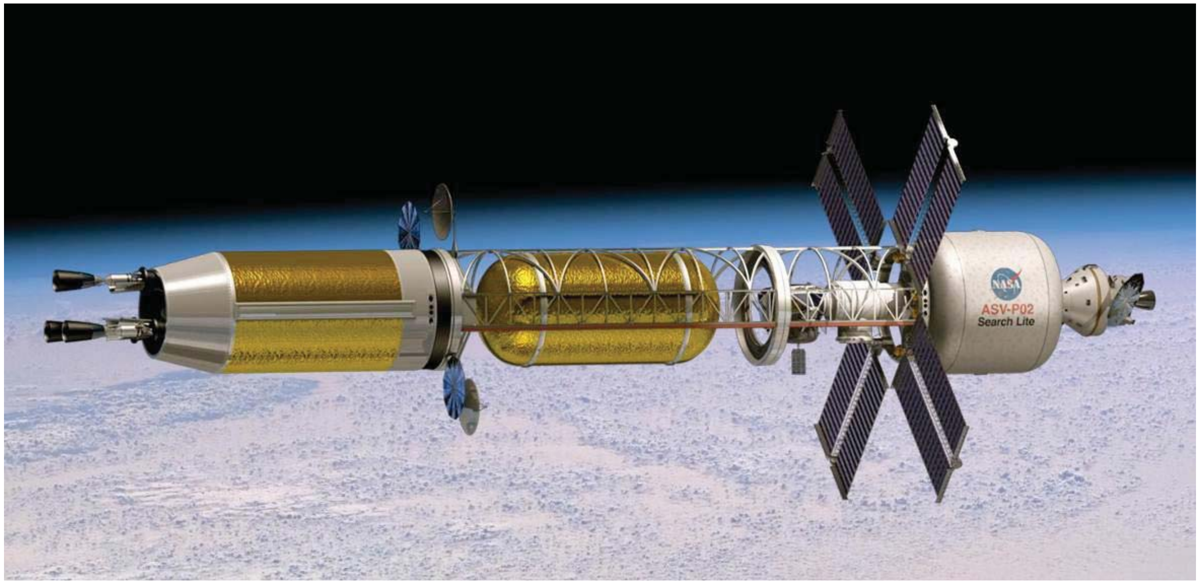


Image Reference [1]

Nuclear Thermal Propulsion Basics

- Chemical propulsion performance limited by available energy stored in chemical bonds
- Nuclear propulsion performance limited by material temperature limitations
- Specific impulse
  - Temperature (T)
  - Molecular Weight (MW)

$$I_{SP} \propto \sqrt{\frac{T}{MW}}$$

- Example
  - Hydrogen/Oxygen
    - MW ~ 13.8 g/mol, T ~ 3420 K, Isp ~480 seconds
  - Nuclear Thermal Hydrogen Propellant
    - MW ~ 2 g/mol, T ~ 2700 K, Isp ~ 900 seconds

Bimodal Basics

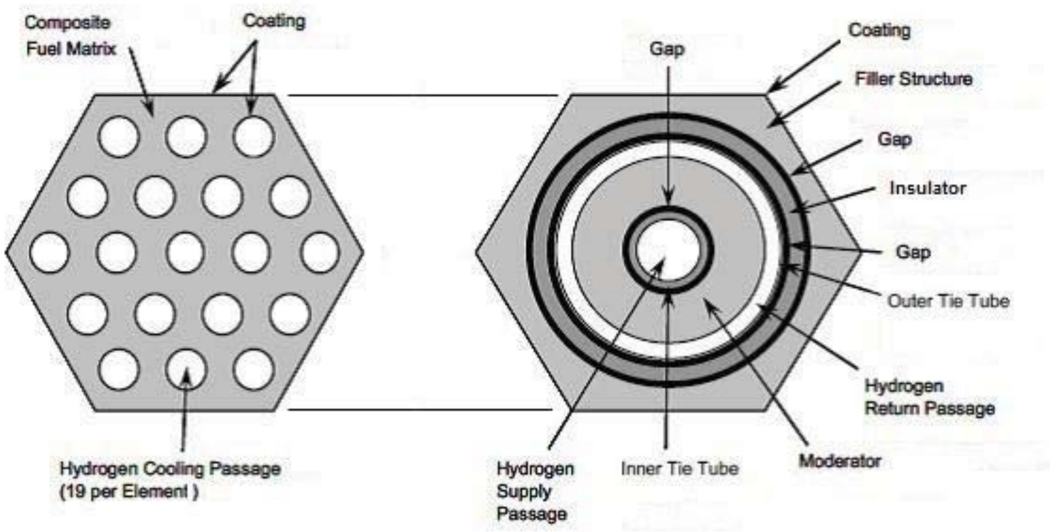
- Reactor core contains high amounts of unused ^{235}U
- Long coast periods of inactivity can be utilized
- Reactor operates at highly reduced power (~1/1000th)
- Tie tubes are used as heat source for closed Brayton power cycle with He-Xe working fluid
- Many Brayton cycle variations possible
- Chose most simple direct heat closed Brayton power cycle without a recuperator in order to reduce complexity and mass

Analysis Methodology

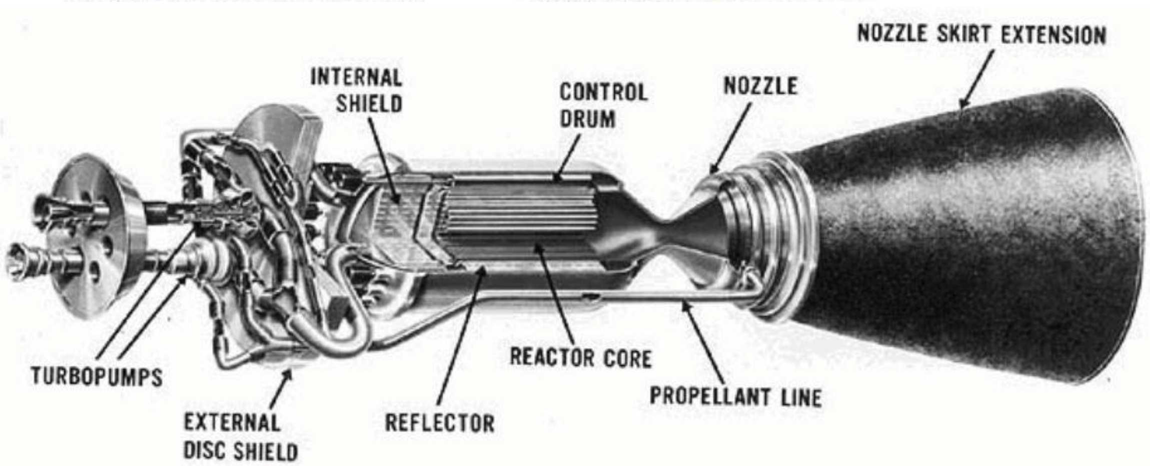
- Propulsion Mode
  - Full system model in NPSS (Numerical Propulsion System Simulation)
  - Steady State Solution
  - Custom Reactor Elements
    - Fuel Element
    - Tie Tube Element
    - 1-D Thermo-Fluid Analysis axial temperature profile
- Power Mode
  - Isolated tie tube model in NPSS
  - Steady State Solution
  - Results from NPSS are fed to BRMAPS to compute Brayton cycle

NERVA SYSTEMS

NERVA Design



a) Typical NERVA Derived Fuel Element   b) Typical NERVA Derived Tie Tube



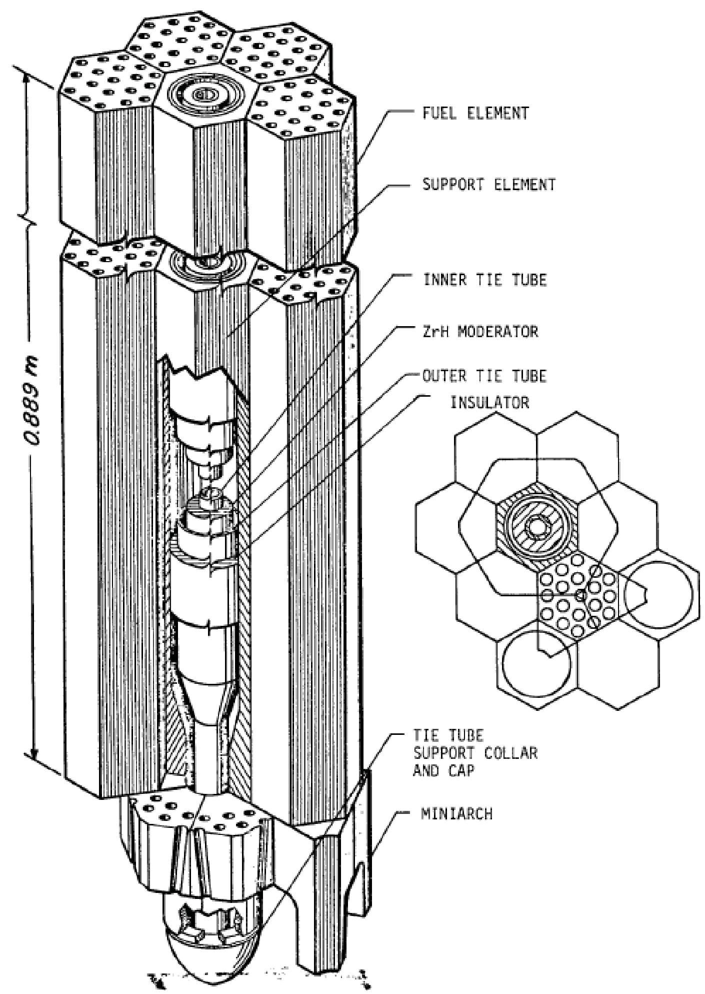


Fig. III-1. Schematic of fuel elements, support elements, and hot-end support hardware.

Image Reference: [3]   Image Reference: [4]

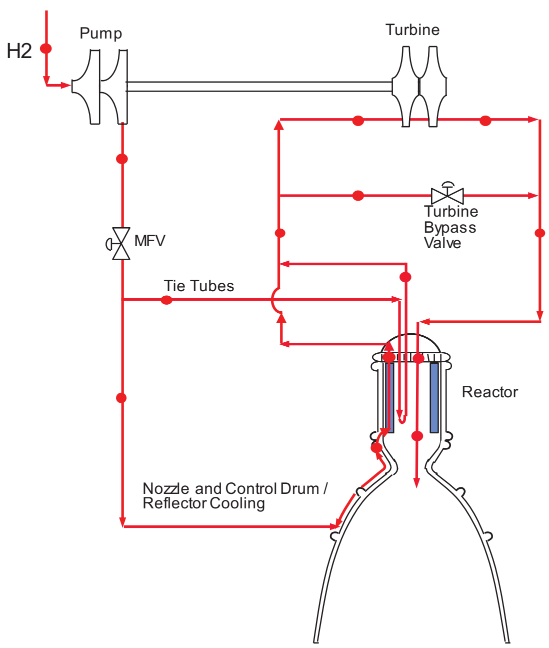
NERVA: Propulsion vs. Power Mode

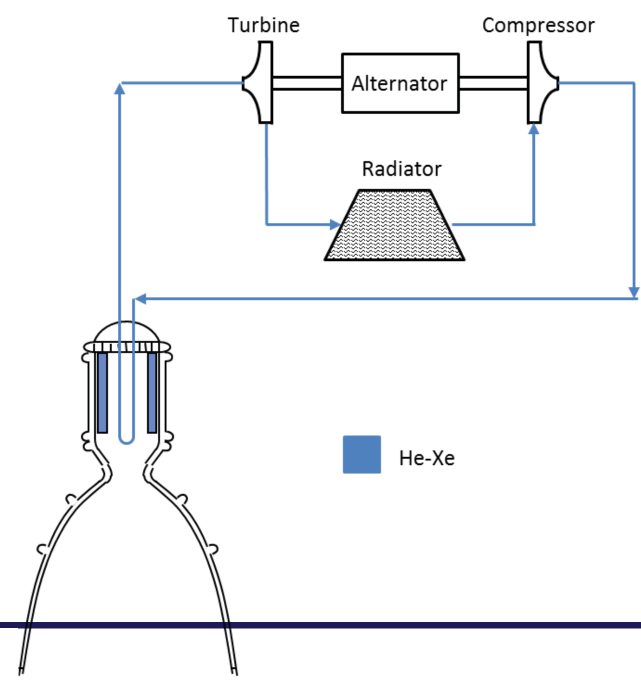
Propulsion Mode

- High Power
- H2 working fluid
- Tie tubes provide power for turbomachinery

Power Mode

- Low Power
- He-Xe working fluid
- Tie tube flow only



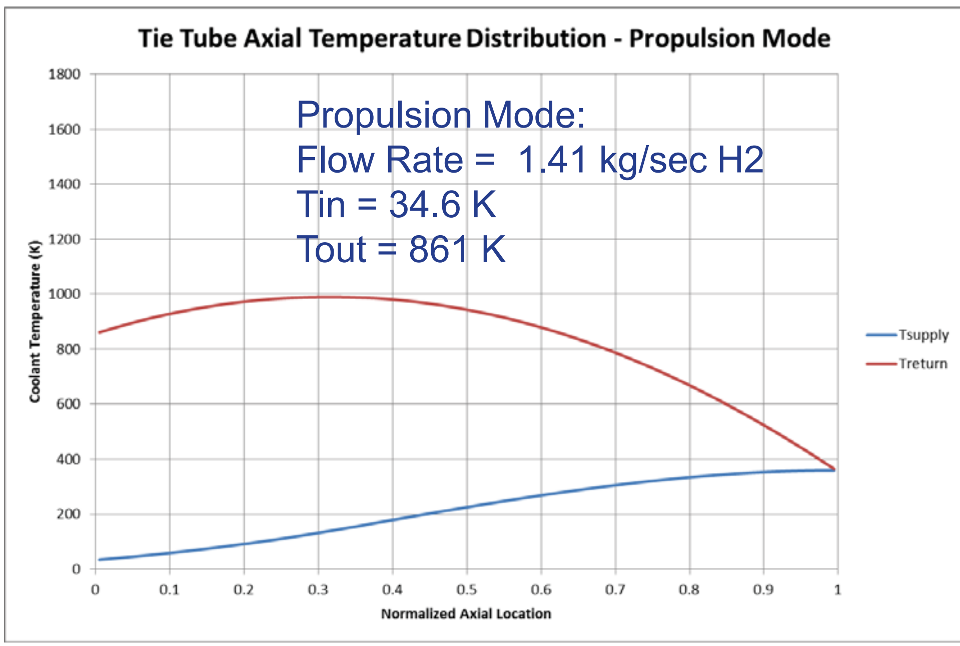


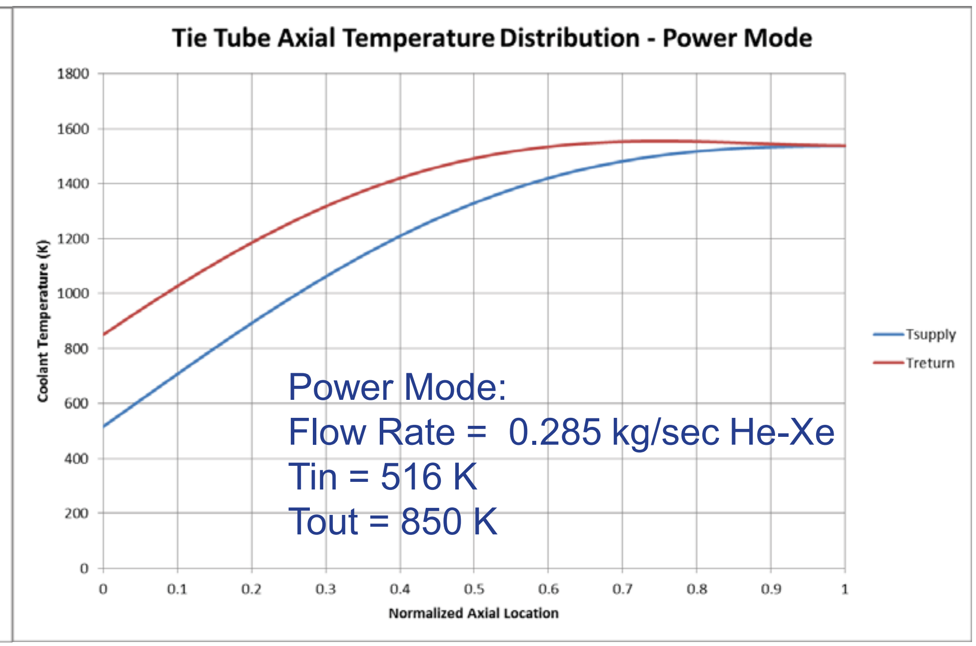
NERVA Limitations During Power Mode

- ZrH moderator material
- Elevated temperatures cause H2 to be released
- Moderator temperature limitation ~< 1000 K
- Potential long term effects on criticality
- Greater concern for power mode
  - Longer duration at elevated temperature
  - He-Xe working fluid
  - Higher temperature moderator

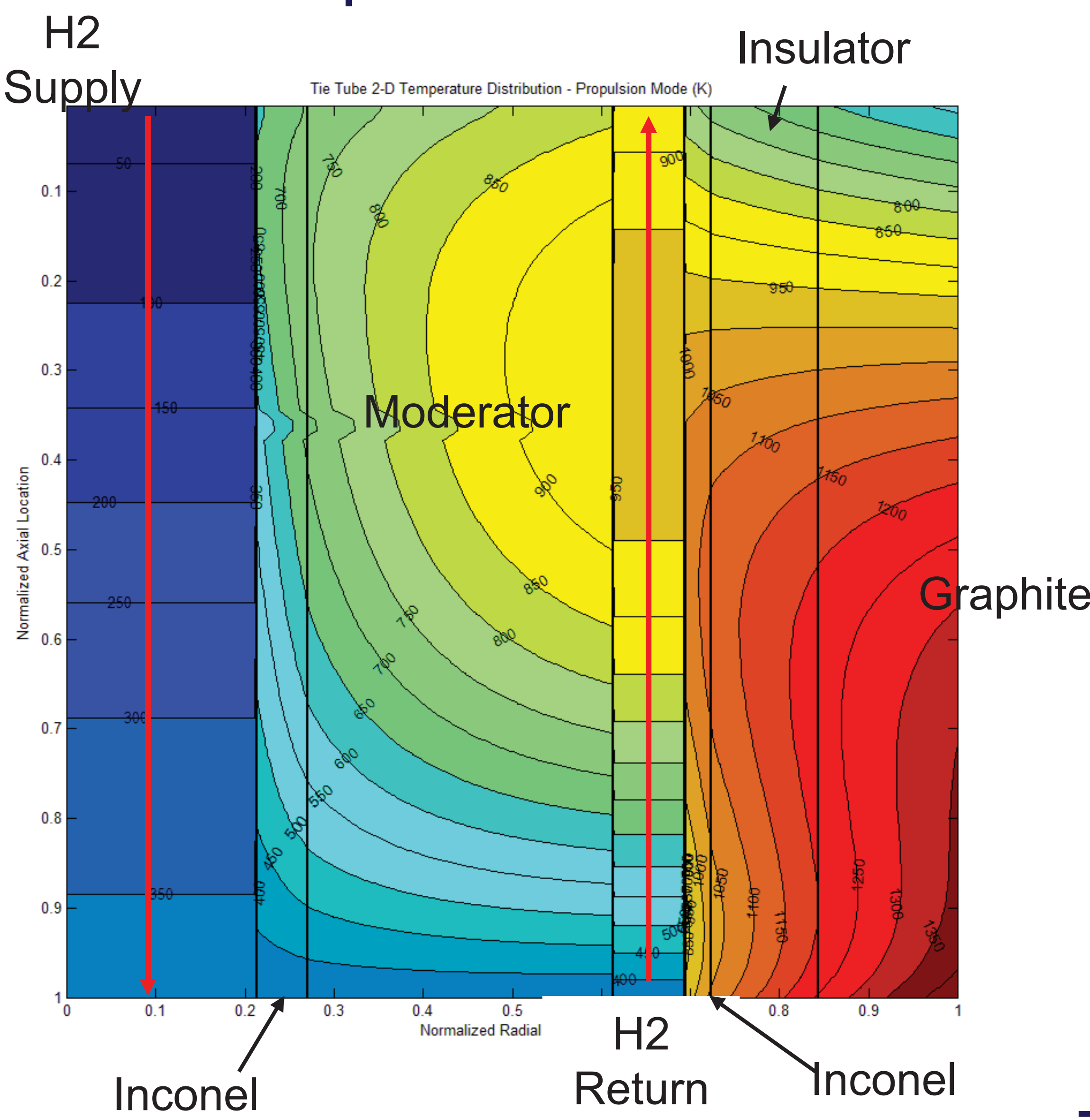
Tie Tube Axial Temperature Profile

- Significant temperature profile difference between power and propulsion
- Results are consistent with previous analysis [5]
- Temperature profile is driven axially rather than radially

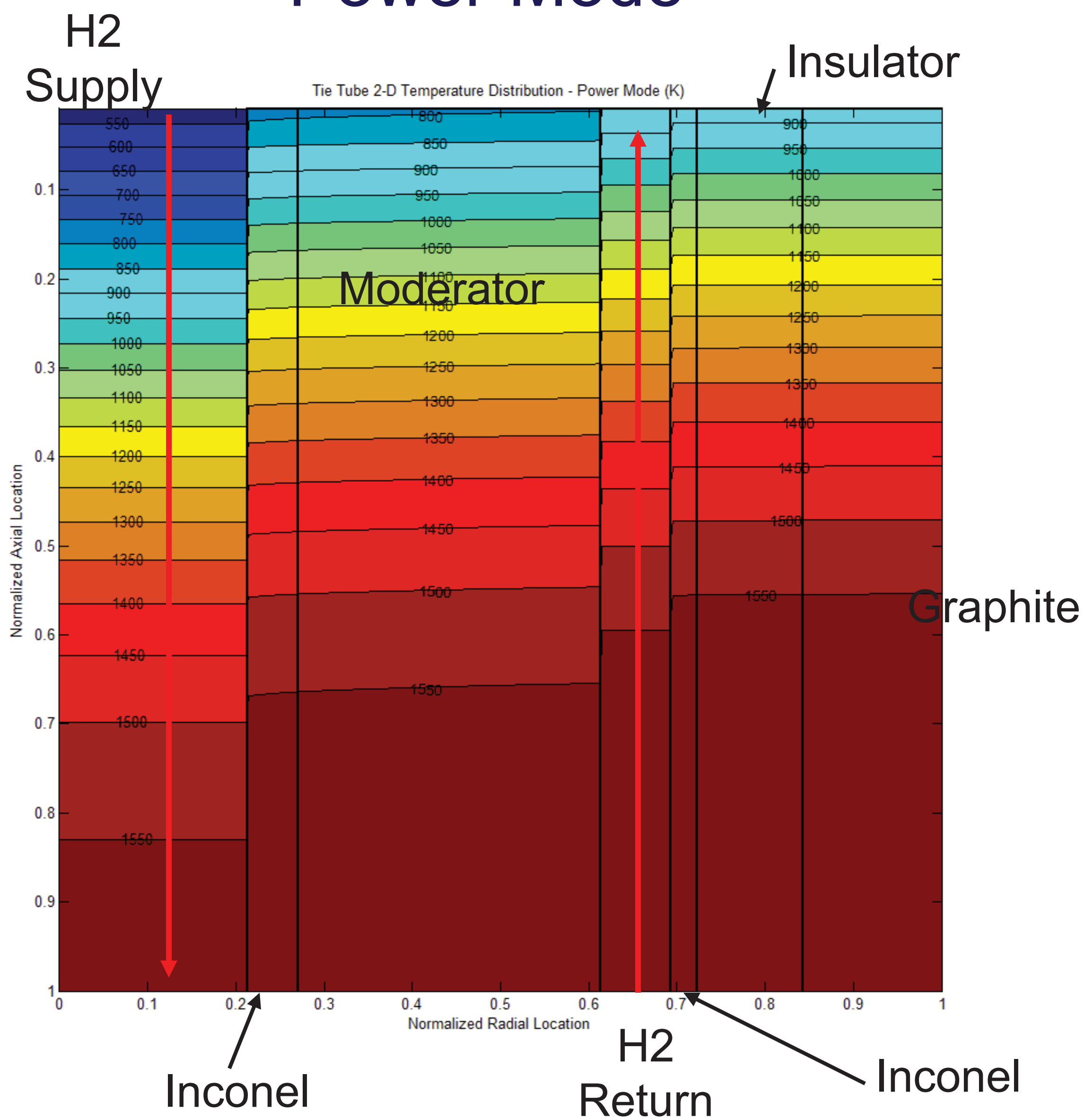




Propulsion Mode



Power Mode


H2
Supply
Tie Tube 2-D Temperature Distribution - Power Mode (K)
Insulator
Moderator
Graphite
H2
Return
Inconel
Inconel
Normalized Axial Location
Normalized Radial Location

Discussion

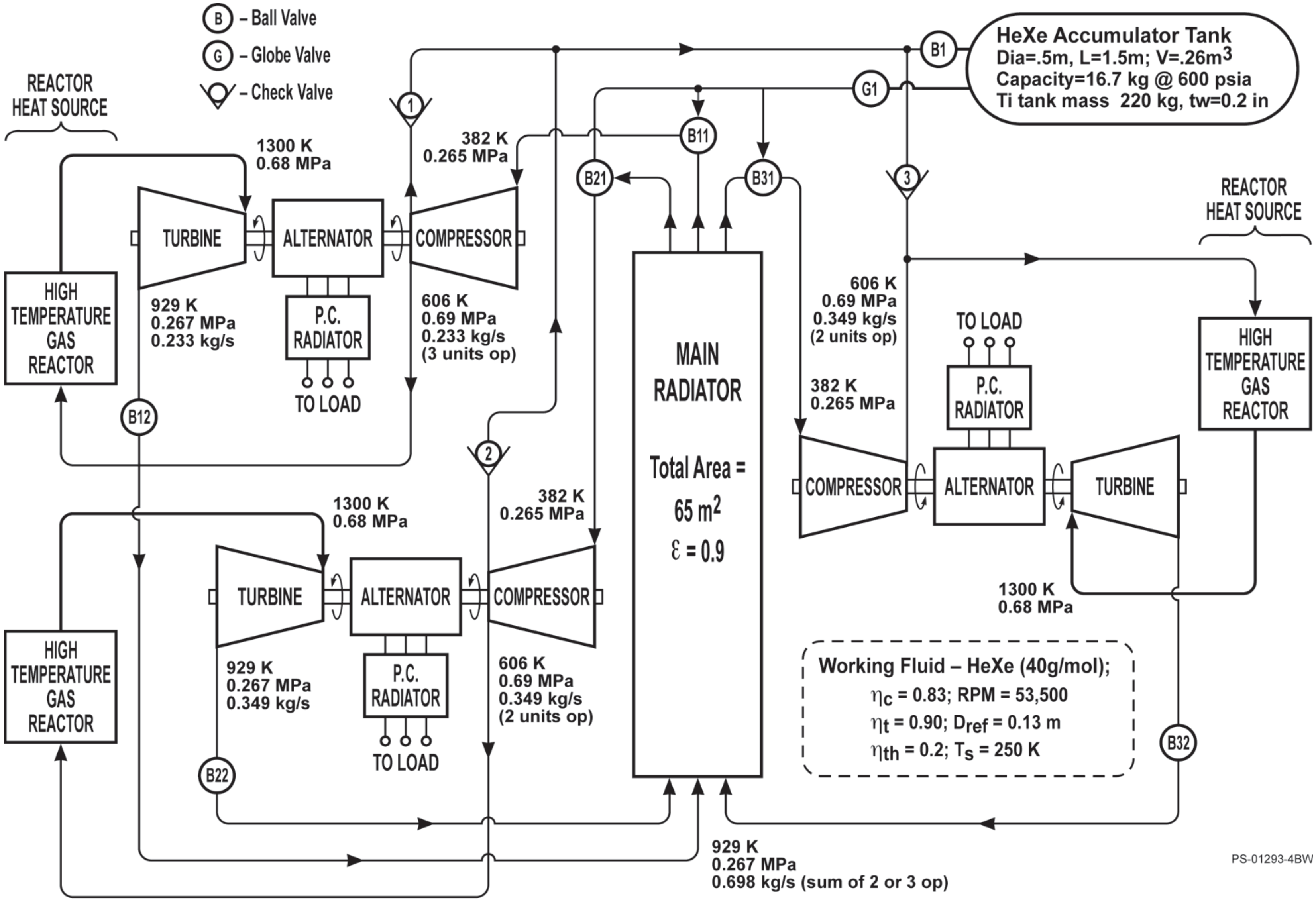
- Lower mass flow rate → Lower heat transfer coefficient, Less Heat Flux
- Thermal gradient driven in axial direction rather than radial direction
- Model assumptions may be less accurate in power mode
  - No conduction axially assumed
  - Results show that axial conduction must be considered
  - Better assumption in propulsion mode due to higher heat fluxes
    - Q_radial >> Q_axial

ESCORT MANNED BIMODAL RESULTS

Escort Manned Bimodal System

- Reactor core based on Escort/TRITON Design
  - 24 inch length
  - Central Energy Transfer Duct (ETD) for power mode
  - Ceramic Metallic (CERMET) fuel
- 3 x 25 klbf engines clustered for propulsion mode
- 3 x 16.67 kWe Brayton rotating units in power mode
  - 25 kWe each, design, to provide 50 kWe in event of failure
  - Common radiator
- Temperature during power mode is not an issue due to materials and geometry

50 kWe System Results - Juhasz



Conclusions

- NERVA Bimodal
  - Differences in operating characteristics between power and propulsion mode as well as the desire for maximum tie tube exit temperature results in temperatures above allowable for power operation in the NERVA reactor.
  - Improper modeling assumptions exaggerate the trend.
  - Look into new materials or design geometry to mitigate (NERVA not designed for bimodal)
- Escort Bimodal
  - Power mode operation seems feasible for a manned mission
  - Temperature during power mode is not an issue due to materials and geometry

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  - Mark Stewart
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  - Jim Fittje
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  - NCPS Project

References

1. Borowski, S., McCurdy, D., and Packard, T., “7-Launch NTR Space Transportation System for NASA's Mars Design Reference Architecture (DRA) 5.0," AIAA-2009-5309, Aug. 2009.
2. Borowski, S.K., McCurdy, D.R., Packard, T.W., “Near Earth Asteroid Human Mission Possibilities Using Nuclear Thermal Rocket (NTR) Propulsion”, AIAA-2012-4209, July 2012.
3. Fittje, J.E., “Upgrades to the NESS (Nuclear Engine System Simulation) Code”, AIAA-2007-5620.
4. “Nuclear Engine Definition Study: Preliminary Report”, LA-5044-MS, Vol. I-III, September, 1992.
5. Clough, J., “Integrated Propulsion and Power Modeling for Bimodal Nuclear Thermal Rockets”, PhD dissertation, 2007.